BJET

(Bayero Journal of Engineering and Technology)

https://bjet.ng/index.php/jet

Research Article
2025, Vol. 20 (1), 26-32

ANALYSIS OF COMPRESSION STRATEGIES AND TRANSPORT OF ETHANE IN GAS AND DENSE PHASE THROUGH PIPELINE

Fatima Muhammad Abubakar[1]

[1]**Department of Chemical Engineering, Bayero University. PMB 3011, Gwarzo Road Kano Nigeria.**

Received: 23-05-2025
Revised: 22-06-2025
Accepted: 23-06-2025
Published: 01-07-2025

Abstract: *This study explores the feasibility of using calcined banana peel (CBP) as a heterogeneous catalyst for biodiesel production from non-edible mahogany seed oil (MSO). The research addresses sustainability and cost concerns of conventional biodiesel production while mitigating ethical issues associated with edible oil feedstocks and environmental impacts of traditional catalysts. The CBP catalyst was prepared and comprehensively characterised using FTIR, SEM-EDS, and BET surface area analysis, revealing a surface area of 527.6* m^2/g *with a pore volume of 0.264* cm^3/g*. The transesterification process was optimised using response surface methodology (RSM) with a central composite rotatable design (CCRD) to determine the effects of reaction time, temperature, methanol-to-oil molar ratio, and catalyst concentration on biodiesel yield. Optimum conditions were determined to be a reaction time of 156 minutes, a temperature of 66°C, and a catalyst concentration of 2.45%. Under these conditions, the maximum experimental biodiesel yield was 59.61%, which compared well with the predicted value of 61.65%. GC-MS analysis confirmed the biodiesel's composition as primarily fatty acid methyl esters (FAMEs), with methyl oleate and methyl linoleate as major components. Analysis of key physicochemical properties demonstrated that the mahogany biodiesel largely meets ASTM standards for fuel quality. These findings demonstrate the potential of CBP as a viable and sustainable heterogeneous catalyst for efficient MSO biodiesel production, offering a promising route to reduce waste, utilise non-edible feedstocks, and enhance biofuel industry sustainability and an 80% faster settling time (from 1.2 s to 0.2 s) compared to the conventional P controllers. Additionally, the stability margin improves significantly, with phase margin increasing from -180° to +0.167°. These findings highlight the efficacy of the FOPI-based control scheme in enhancing STATCOM system performance, particularly in mitigating ripple and improving transient response speed*

Key words: Biodiesel, Heterogeneous catalysts, Mahogany seed oil, Optimization, Response Surface Methodology, Transesterification

1 Introduction

Ethane is the second major component of natural gas, following methane, and is an important feedstock in various industrial processes. It is primarily found in natural gas deposits and is typically separated during the processing of natural gas into natural gas liquids (NGLs). Natural gas liquids are gaseous hydrocarbons heavier than methane that are extracted in liquid form during the natural gas processing phase. Ethane is a key component of NGLs and plays a crucial role in the production of ethylene, a versatile chemical used in a range of products, including vinyl acetate monomer (VAM) used to produce adhesives, paints, coatings, and textiles (Karim and Adris, 2000). Ethane is also employed as a refrigerant in cryogenic refrigeration schemes due to its thermodynamic properties, which make it suitable for low-temperature cooling applications in industrial processes.

In recent years, there has been a marked increase in demand for ethane, particularly driven by the expansion of the petrochemical industry, where it is used in the production of ethylene and its derivatives. Consequently, ethane is now produced industrially using various methods, including steam cracking of naphtha and heavy fuels, adsorption from natural gas using packed bed absorbers, membrane separation, and cryogenic separation processes. Cryogenic separation is particularly important as it involves cooling natural gas to extremely low temperatures, typically around -85°C, to separate ethane from methane and other lighter hydrocarbons (Menwer, 2013).

However, ethane is not always produced in locations where its demand is high. As a result, there is a need for effective transportation methods to move ethane to market sources or areas with greater demand. Ethane can be transported in two primary phases: dense phase and gas phase. In the dense phase, ethane is compressed to a pressure above its critical pressure approximately 5.0 MPa and maintained at a temperature below its critical temperature approximately 34°C. In this state, ethane exhibits a unique combination of gas-like and liquid-like properties, making it an efficient medium for transport (Moshfeghian, 2014).

Pipelines are the most common mode of transportation for ethane, with various lengths and diameters used depending on the distance and terrain. Pipeline design is a critical factor in ensuring the safe and efficient transportation of ethane. It must account for the correct pressure, temperature, and volume of ethane being transported, as well as potential variations in these parameters over the pipeline’s operational life. Major components of pipeline systems include the pipeline itself, compressor and pump stations, monitoring and control facilities, valves and regulators, and gate settings and rights-of-way corridors (Tabkhi et al., 2010).

Several key variables must be considered when designing ethane pipelines, such as pipeline properties (e.g., diameter and length), the characteristics of the transported material (e.g., specific gravity, temperature, and pressure), and environmental conditions. All these factors are integrated into models used to optimize pipeline design.

While previous studies on pipeline design have predominantly focused on methane, much of the work has concentrated on optimizing flow rates and minimizing pressure drops. Although improvements in pipeline materials and compressor technologies have enhanced the efficiency of methane transportation. There are still a few studies on the optimization of ethane pipeline design (Dinh et al; (2021) Wenlong et al; (2022))

This study builds upon these previous insights by extending the analysis to the transportation of ethane, specifically addressing the differences in the dynamics of dense-phase versus gas-phase ethane. In addition to the evaluation of phase behavior, this research explores advanced compression strategies and the optimization of pipeline diameters to minimize costs while ensuring safe and efficient transport of ethane. By considering the unique transport properties of ethane compared to methane, the study aims to provide a detailed, comparative analysis of transportation strategies that can improve operational efficiency and reduce costs for the ethane industry.

2 Methodology

2.1 Development of Models

Optimization of pipeline design involves the right selection of diameter (and/or geometry) for a certain flow rate of gas to be transmitted. In this work the amount of ethane to be transported, length of the pipeline and the outlet pressure are assumed to be fixed. The flexible parameters are the pipeline diameter and the inlet pressure, the effect of changing the inlet pressure and pipe diameter on pipeline segments was studied using FORTRAN language.

FORTRAN language was used to create model used in calculating the power required by booster stations, the software contains subroutines that enable computation of number of stations along pipeline and accordingly calculates pressure, temperature and velocity profiles at a given gas property. When using this model, it is assumed that the flow is steady, there is no significant change in elevation along the pipeline, booster stations are designed to boost pressure when it falls below the outlet pressure. The variables input in the model are inlet pipeline temperature, inlet pressure, outlet pressure, pipeline length, flow rate and diameter.

The inlet and outlet pipeline conditions (temperature and pressure) were chosen based on the phase the fluid is to be transported, while the flow rate and length of the pipeline were fixed at 7kg/s and 38 km respectively. A standard velocity-flow equation for a fluid (Chandel, Pratson et al. 2010) was used to calculate the pipe diameter. This gave an idea of what the pipeline diameter would be.

$$D = \sqrt{\frac{4Q}{\pi U}} \qquad (1)$$

The mass flow rate (kg/s) is converted to volumetric flow rate ($m^3\,/s$) by dividing with density of liquid ethane at atmospheric pressure (546 kg/m^3). U the fluid velocity designed for the pipe assume is 1.0 (m/s).

When using equation (1), the maximum operation pressure was assumed to be 10MPa; the minimum yield strength of the pipe, S, was assumed to be 483 MPa (for X 70 steel); the safety design factor taken as F = 0.72 and E = 1.0 for seamless pipes

After the pipeline geometry has been determined, the next step is to determine the number of booster stations and the length between the stations based on pressure drop along the pipeline. The length of pipeline segment was determined using Equation (2) for frictional pressure drop in isothermal compressible flow (Chandel, Pratson et al. 2010) given by

$$\Delta p = D_f \frac{\rho U^2}{2}\frac{l}{D} \qquad (2)$$

D_f is the Darcy friction factor, U velocity (m/s), length and D diameter, ρ is density (kg/m3).

The number of pipeline segment N_s is total pipeline length Lp divided by the length of pipeline segment L_i :

$$N_s = \frac{L_p}{L_i} \qquad (3)$$

2.2 Thermal Pipeline Hydraulics

In order to predict pressure drop and change in temperature along the length of the pipeline the following set of nonlinear algebraic equations must be solved numerically (Martynov 2014):

The integral form of momentum equation given by:

$$p_i^{in} - p_i^{out} = \frac{fG^2}{2\rho A^2}\frac{l_i}{D} \qquad (4)$$

where ρ is the average density along the length of the pipeline.

Another equation is the integral energy balance equation given by:

$$T_i^{out} - T_i^{in} = \frac{4q_{w,i}}{\rho u.c_p}\frac{l_i}{D} \qquad (5)$$

$$\rho = \rho\,(p_{ave}, T_{ave}) \qquad (6)$$

$$p_{ave} = 0.5.(p_{in} + p_{out}) \qquad (7)$$

And the outlet pressure is defined as:

$$T_{out} = T(P_{out,} h_{out}) \qquad (8)$$

And h_{out} is calculated using

$$h_i^{out} - h_i^{in} = \frac{4q_{w,i}}{\rho u.c_p}\frac{l_i}{D} \qquad (9)$$

And heat flux is given by:

$$p_w = \alpha(T_{amb} - T_{ave}) \qquad (10)$$

2.3 Cost Analysis

Pipeline systems consist of two basic components of cost; they are capital cost of pipeline and annual operating costs (Menon 2005).

2.3.1 Pipeline Capital Cost

The capital cost consist of major components like: pipeline, compressor stations, mainline valve stations, pressure regulator stations, SCADA and telecommunication, environmental and permitting, right of way acquisitions and engineering and construction management (Menon 2005). For simplicity in this work the pipeline and compressor / pump station were considered as the components of capital cost.

The pipeline cost was calculated based on length, outside diameter, pipe wall thickness, the cost of the total pipe material is obtained using equation (4)

$$PMC = 0.0246\,(OD - t)\,tLC \qquad (11)$$

PMC is the pipe material cost ($), L length of pipe (km), OD is the outside diameter, t is the pipeline thickness (mm), pipe material cost, $/metric ton.

The cost of installing a compressor station was obtained based on an all-inclusive price of dollars per installed HP. Assumption of an installation cost of $250 per kW was made, therefore

$$C_{cst} = C_i \times P_c \qquad (12)$$

C_{cst} is the installed cost of compressor station, C_i is the installation cost of compressor per horsepower, P_c is the power required by compressor.

While that of pump is

$$C_{pst} = C_i \times P_p \qquad (13)$$

C_{pst} is the installed cost of pump station, C_i is the installation cost of pumps per horsepower, P_p is the power required by pump.

2.3.2 Pipeline operating cost

After the pipeline has been constructed the next cost to determine is the annual operation cost over the useful life of the pipeline. It comprises of the following, compressor/pump station fuel or electricity cost, maintenance and repair cost for both the pipeline and compressor/pump, utility cost, periodic environmental and permitting costs, right of way costs, administrative and payroll costs and SCADA and telecommunication (Menon 2005). For simplicity, only the fuel operating cost for compressors and electric cost for pumps are considered account for other operating costs the operating cost was increase by a factor 50% of Annual demand charge and pump station electric power cost.

2.3.3 Compressor/Pump stations operating cost

Assuming electricity cost 10 cent/kilowatt hour (cent/kWh), and the station operates 24- hour-a- day and 350 days a year annual cost is calculated based on equation (Menon 2005) (14)

$$P_{SEC} = P_p \times 1000 \times h_r \times N_D \times C_E \qquad (14)$$

PSEC is the pump station electric power cost, PP is the pump power in horsepower, ND is the number of days the plant operate, hr hours the plant operates in a day, CE is the cost of electricity/kWh.

$$C_{SEC} = C_p \times 1000 \times h_r \times N_D \times C_E \qquad (15)$$

Compressor station electric power cost CSEC is calculated from equation (15). Where CP is the compressor power in horsepower, ND is the number of days the plant operate, hr hours the plant operates in a day, CE is the cost of electricity/kWh

Utility companies charge about $5/kW/month, demand charge for starting and stopping electric motors (Menon 2005). Annual demand charge will be

$$A_{Dc} = P \times C_U \times N_{mth} \quad \ldots \qquad (16)$$

Where ADC is the annual demand charge, P is the pump or compressor power, Cu cost of utility per month, N_{mth} is the number of months.

To obtain the annual operating cost, the sum of the power required by the stations and the utility cost per month add 50% of the sum to account for other operating costs like operation and maintenance.

$$OPC = P_{SEC} + A_{Dc} + 50\%(P_{SEC} + A_{Dc}) \qquad (17)$$

Where OPC is the annual operating cost, ADC is the annual demand charge, and PSEC is the pump station electric power cost.

$$OPC = C_{SEC} + A_{Dc} + 50\%(C_{SEC} + A_{Dc}) \qquad (18)$$

Where OPC is the annual operating cost, ADC is the annual demand charge, and CSEC is the compressor station electric power cost. To obtain the present value of this operating cost we assume a project life of 20 years and 8% interest rate to perform a discount cash flow analysis.

$$(PV_{OC}) = \frac{R}{i}\left(1 - \frac{1}{(1+i)^n}\right) \qquad (19)$$

PV_{OC} is the Present value of operating cost, R is series of cash flow flows, i is the interest rate, and n number of periods. The sum of the present value of operating cost and capital cost gives the present cost (present value) of the pipeline.

$$PV = C_c + PV_{OC} \quad \ldots \qquad (20)$$

Where PV is the Present value and Cc is the capital cost

3 Result and Discussion

3.1 Effect of inlet pressure on number of pipeline segments

Increase in inlet pressure results in corresponding decrease in the number of pipeline segments, in both gas and dense phase. A decrease in power required to transport gas through the pipeline was also observed.

3.1.1 Dense phase

Pressures decrease as ethane travels through the pipeline. However, the higher the inlet pressure the longer the length of the pipeline segment. At a discharge pressure of 70 bar the length of the pipeline segment was 11km, when the discharge pressure was increased to 80 bar the length of the pipeline segment increases to 17 km, a further increase in discharge pressure of up to 90 bar results in an increase in the length of the pipeline segment to 23 km. An increase in the length of the pipeline segment resulted in a decrease in the number of pipeline segments from 3 at 70 bars, to 2 at 80 bars up to 1 at 90 bars as seen in Table 1.

Table 1: Effect of varying inlet pressure on number of pipeline segments on a 0.1m pipeline

Diameters (m)	Inlet pressure (bar)	Outlet pressure (bar)	Number of segments	Power (MW)
0.1	70	50	3	0.119
0.1	80	50	2	0.115
0.1	90	50	1	0.075

The inlet temperature is 298 K, when ethane passes through the pipeline this temperature decreases to 293 K, 291 K and 290 K as it travels through a pipeline due to heat exchange with the environment. Maintaining ethane at this temperature allows it to travel through the pipeline in the dense phase.

Similar result was seen when transporting ethane in gas phase using a 0.15m pipeline, although the diameter of the pipelines used is not the same, as inlet pressure increase from 30 to 35 and then 40 bar, number of pipeline segments decreases. This was attributed to an increase in the length of the segments as inlet pressure increases.

The length of segment increases from 3 km at 30 bar, to 9 km at 35 bar and 17 km at 40 bar. And the number of segments decreases from 11 to 4 and then further decreases to 2, as seen in Table

Table 2: Effect of varying inlet pressure on the number of pipeline segments using a 0.15 m pipeline

Diameters (m)	Inlet pressure (bar)	Outlet pressure (bar)	Number of segments	Power (MW)
0.15	30	25	11	0.81
0.15	35	25	4	0.51
0.15	40	25	2	0.46

Like the dense phase, the inlet temperature was also set at 298k, when ethane gas passes through the pipeline temperature decreases to 285 K, 271K and 264 K. This decrease in temperature of ethane was caused by the expansion of ethane as it travels through the pipeline.

From the results, pumping ethane at high pressure reduces the number of booster stations and the power required to pump ethane. But for safety reasons, the pressure required transport ethane must be kept below the maximum allowable pressure of the pipeline. To prevent rapture or leakage from the pipeline.

3.1.2 Effect of pipeline diameter on number of segments

It was discovered that the increase in pipeline diameter results in decrease in pressure drop and subsequent reduction number of booster stations required to transport ethane gas,

Table 3 demonstrates a similar relationship for dense-phase ethane transport. For a discharge pressure of 90 bar and a suction pressure of 50 bar. A pipeline diameter of 0.1 m results in a single segment, consuming 0.075 MW of power. While reducing the diameter to 0.09 m increases the number of segments to 2 and doubles the power requirement to 0.150 MW. A further reduction to 0.08 m increases the number of segments to 5, with a power demand of 0.375 MW.

Table 3: Effect of varying pipeline diameter on number of pipeline segments for ethane transported in dense phase

Diameters (m)	Inlet pressure (bar)	Outlet pressure (bar)	Number of segments	Power (MW)
0.1	90	50	1	0.075
0.09	90	50	2	0.150
0.08	90	50	5	0.375

The results indicate that smaller diameters exacerbate the number of segments needed due to higher pressure losses along the pipeline. Moreover, the cost analysis (Figure 1) shows that reducing the pipeline diameter increases costs disproportionately. For instance, the cost drops from $233 million at 0.08 m to $47.4 million at 0.1 m.

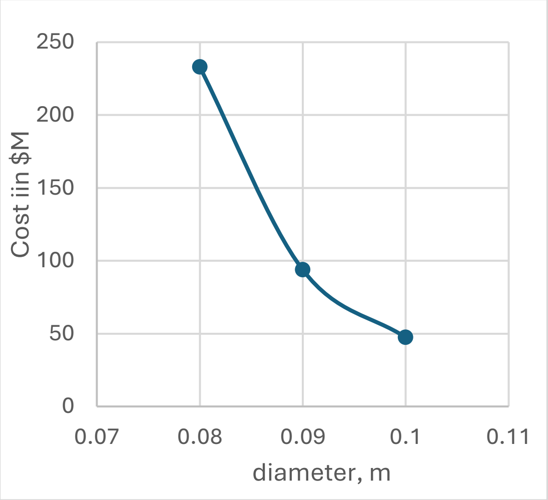

Figure 1: Cost as a function of pipeline diameter (dense phase)

3.1.3 Gas phase

The data in Table 4 highlights how varying the diameter of a pipeline affects the number of segments required for gas-phase ethane transport. With an inlet pressure of 40 bar and outlet pressure of 25 bar, the number of segments decreases as pipeline diameter increases. At 0.15 m, 2 segments are needed, consuming 0.46 MW of power. While at 0.16 m, the number of segments drops to 1, with power reduced to 0.19 MW. At 0.18 m, no segments are required, and power consumption effectively falls to 0 MW.

This trend underscores the importance of larger diameters in reducing operational costs and increasing efficiency. Larger pipelines reduce flow resistance, thereby requiring fewer segments and less power. Figure 2 further illustrates that as pipeline diameter increases, the cost of operation decreases significantly, enhancing economic feasibility.

Table 4: Effect of varying pipeline diameter on number of pipeline segments for gas phase ethane

Diameters (m)	Inlet pressure (Pa)	Outlet pressure (Pa)	Number of segments	Power (MW)
0.15	40	25	2	0.46
0.16	40	25	1	0.19
0.18	40	25	0	0

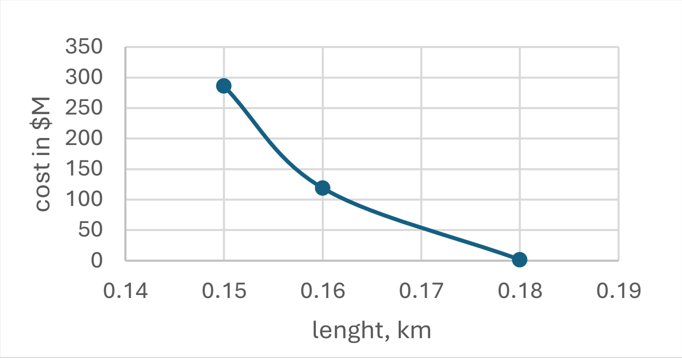

Figure 2: Cost as a function of pipeline diameter (gas phase)

Both figures demonstrate that increasing the pipeline diameter reduces costs. However, the capital expenditure required for larger diameters must be balanced against the reduction in operational expenses. For long-term projects, larger diameters may offer greater financial benefits due to their lower power requirements and reduced need for booster stations.

3.1.4 Comparing Dense-Phase and Gas-Phase Transport

When comparing dense-phase and gas-phase transport, significant differences in power requirements and cost-efficiency emerge. For instance, for a pipeline configuration with two segments, the power required for dense-phase transport is 0.115 MW, while gas-phase transport requires 0.46 MW—four times higher. This disparity arises from the fact that dense-phase transport utilizes pumps, which consume less power compared to the compressors used in gas-phase transport.

Dense-phase transport is generally more energy-efficient and cost-effective than gas-phase transport for the same pipeline configuration. However, gas-phase transport may still be necessary in scenarios where dense-phase operation is not feasible due to limitations in temperature or pressure constraints.

3.1.5 3.3. Environmental Impact

The energy required for ethane transport contributes to greenhouse gas emissions, especially if sourced from non-renewable energy. Dense-phase transport, with its lower energy requirements, presents a more environmentally friendly option compared to gas-phase transport. Additional measures, such as renewable energy-powered pumps and compressors, could further reduce emissions.

4 Conclusion

The findings of this study highlight the critical factors influencing the efficiency of ethane transport pipelines. Optimizing inlet pressure and pipeline diameter can significantly reduce operational costs and energy consumption. Dense-phase transport emerges as the superior choice under most conditions, combining energy efficiency with lower long-term costs. However, the choice between dense-phase and gas-phase transport should be guided by project-specific considerations, including technical feasibility, environmental impact, and economic constraints.

The proposed optimal configuration for this study 7 kg/s ethane transport over a 38 km pipeline with a discharge pressure of 90 bar and a 0.1 m diameter is both cost-effective and operationally efficient. Future studies could explore advanced materials and pipeline coatings to further enhance efficiency.

References

Chandel, M. K., L. F. Pratson and E. Williams (2010). "Potential economies of scale in CO2 transport through use of a trunk pipeline." Energy Conversion and Management 51(12): 2825-2834.

Haugland, C. B.-S. D. (2011). "Optimization methods for pipeline transportation of natural gas with variable specific gravity and compressibility." springer 21: 524–541.

Karim, K. and A. E. M. Adris (2000). Method for producing vinyl acetate monomer from ethane or ethylene oxidation, Google Patents.

Solomon Brown, Sergey Martynov, Haroun Mahgerefteh, Michael Fairweather, Robert M. Woolley, Christopher J. Wareing, Samuel A.E.G. Falle, Heike Rutters, Auli Niemi, Yong Chun Zhang, Shaoyn Chen, Jacob Besnebat, Nilay Shah, Niall Mac Dowell, Christophe Proust, Regis Farret, Ioannis G. Economou, Dimitrios M. Tsangaris, Georgios C. Boulougouris, Jeroen Van Wittenberghe, (2014), CO2QUEST: Techno-economic Assessment of CO2 Quality Effect on Its Storage and Transport, Energy Procedia, Volume 63, Pages 2622-2629,

Menon, E. S. (2005). Liquid Pipeline Hydralics, Marcel Dekker, Inc.

Menon, S. (2005). Gas pipeline hydraulics. CRC Press. 21: 100–120.

Menwer A, M. A.-K., Tahani Saieq, Hans-Jörg Bart (2013). "Ethane production plant for better energy integration and cost reduction in jordan." Journal of Chemical Technology and Metallurgy 48(3): 265-278.

Moshfeghian, M. (2014). "Transportation of ethane by pipeline in the dense phase." PetroSkills John M. Campbell Retrieved 6/07, 2014, from http://www.jmcampbell.com/tip-of-the-month/2014/03/transportation-of-ethane-by-pipeline-in-the-dense-phase/.

Tabkhi, F., L. Pibouleau, G. Hernandez-Rodriguez, C. Azzaro-Pantel and S. Domenech (2010). "Improving the Performance of Natural Gas Pipeline Networks Fuel Consumption Minimization Problems." Aiche Journal 56(4): 946-964.

Dinh Duc Nguyen, F.A. Atiku, Vahid Pirouzfar, Chia-Hung Su (2021). "Technical, economic and thermodynamic analysis for loading, storing, unloading and transporting of Ethane fluid" Journal of the Taiwan Institute of Chemical Engineers,Volume 120, Pages 218-228

Wenlong Jia, Yuanrui Zhang, Changjun Li, Xia Wu, Shuoshuo Song, Fan Yang,(2022). Optimal diameter of liquid-phase ethane transportation pipeline considering the liquid-vapor phase change,Journal of Natural Gas Science and Engineering,Volume 107,